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# INVESTIGATION OF PHASE VELOCITIES OF LONG PERIOD SURFACE WAVES AND FOCAL MECHANISM STUDIES

William Stauder, S.J., and Otto Nuttli  
SAINT LOUIS UNIVERSITY  
St. Louis, Missouri

Contract No. AF 19(604)-7399

Project No. 8652

Task No. 865201

## Final Report

Period covered: August 1, 1960 - August 31, 1965

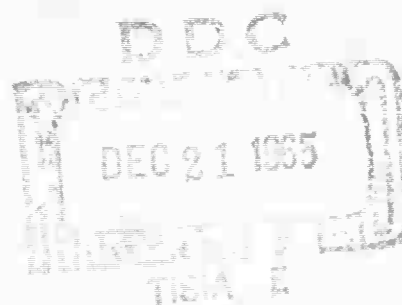
September 1965

Prepared for

Air Force Cambridge Research Laboratories  
Office of Aerospace Research  
United States Air Force  
Bedford, Massachusetts

WORK SPONSORED BY ADVANCED RESEARCH PROJECTS AGENCY  
PROJECT VELA-UNIFORM

ARPA Order No. 292, Amendment 7  
Project Code No. 3810, Task 2



474981

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## ABSTRACT

The research conducted under this contract concerned eight general areas of investigation:

1. Establishment of a network of seismic stations in the central U.S. suitable for the study of long period surface waves and other specialized studies.

2. Phase and group velocity studies of surface waves. These include phase velocity determinations of both Love and Rayleigh waves, inversion of the velocity data, group velocities of very short period Rayleigh waves, and group velocities along paths which cross the Caribbean Sea.

3. Reduction of ground motion to motion in the incident wave. Theoretical work by Haskell has been verified from observational data and further developed to study angles of incidence of P waves and polarization of S waves which traverse a multilayered crust. Crustal transfer functions for various crustal models have been determined and used to study the effect on ground motion of changes in crustal parameters.

4. Focal mechanism determinations. Radiation patterns of P and S waves are found to be characteristic of given earthquake sequences and, to some degree, of given earthquake regions.

5. Focal depth. The  $P_g$ - $P_n$  vs  $S_g$ - $P_g$  method has been found of qualitative help in studying focal depth of shocks in SE Missouri. The transfer function for a source in a layered medium has further shown that at shallow depths the source-crust system acts as a rejection filter for the low frequency portion of the spectra of body waves.

6. Inversion of body wave data. The transfer function of  $TW/TU$  (ratio of vertical to horizontal ground motion) has been calculated as a function of a dimensionless frequency for representative one- and two-layer crustal models. Spectra of observed P waves are then compared to the theoretical curves to determine crustal structure.

7. Effect of low velocity channels on travel times. Parameters of a low velocity channel have been systematically varied to examine the circumstance under which the channel produces or does not produce a shadow zone. BILBY and GNOME data were

then examined to study lateral variations in upper mantle velocities throughout the central, eastern, and western U. S.

8. Local crustal structure, seismicity,  $P_n$  velocity.

A brief discussion of work accomplished is given in the body of the report, followed by abstracts of papers published.

## Introduction

The research conducted under this contract concerned eight general areas of investigation:

1. The establishment and operation of a quadrilateral network of seismograph stations in the central United States.
2. Phase and group velocity studies of seismic surface waves.
3. Reduction of ground motion to motion in body waves incident at the base of the crust.
4. Focal mechanism studies.
5. Focal depth of seismic sources.
6. Inversion of body wave spectra to determine crustal structure.
7. Effect of low velocity channels on travel times of seismic waves.
8. Local crustal structure, seismicity,  $P_n$  velocity.

The results which have been forthcoming from these investigations have, for the most part, been published in a series of papers. A list of these papers may be found at the end of this report. In the body of the report we shall first give a brief discussion of the results of the research under each of the areas of investigation mentioned above. This discussion will be followed by the abstracts of the papers.



## 1. Discussion of Results.

1.1 Network of Seismograph Stations. A quadrilateral network of seismic stations, similar in instrumentation to the WWSS system was established at Manhattan, Kansas, Rolla, Missouri, Dubuque, Iowa, and Bloomington, Indiana. A series of calibration experiments was performed in order to select the instrumental constants most appropriate for the recording of S waves and mantle Rayleigh waves, that is, waves in the period range of 10 seconds to 100 seconds and longer. The network has been essential for the supply of data for the long-period P, S, and surface wave studies described below.

In addition to contract-related work, copies of records and other data have routinely been supplied to the USCGS and to other VELA-Uniform users for NTS and events of similar type. A phenomenon which has been noted, but thus far not investigated further, is an early arrival, prominent on the short-period vertical record at Manhattan, for NTS events. This arrival is about 4 seconds earlier than the expected time of arrival of  $P_n$ ; the latter phase is also a prominent arrival.

Two long-playing short-period seismic stations have been installed in trailers for temporary use in the SE Missouri seismic zone, and for the recording of other events of interest.

1.2 Phase and Group Velocity Studies. Our primary studies concerned phase velocities in a mid-continental region. These studies have been supplemented by certain other surface wave investigations.

In the central United States, over the area of the St. Louis University network, phase velocities of both Rayleigh and Love waves have been measured for the period range 5 to 80 seconds. These data are of significance for two reasons. First, while the Love wave phase velocities in the period range considered were found to be comparable to those determined by Brunc and Dorman for the Canadian Shield, the Rayleigh wave phase velocities are notably lower (3%) in the central U.S. than those in the Canadian Shield. Second, an inversion program designed to determine a crust-upper mantle model which would fit both the Love and the Rayleigh wave phase velocity data was unsuccessful in achieving a simultaneous fit to the two kinds of data. Anisotropy seems to be required in the upper mantle. This is in contrast to the situation which prevails in the Canadian Shield. These results indicate a need for further work in order to investigate a) the transition between the Canadian Shield structure and the central U.S., b) the dimensions of areas over which phase velocities are constant, c) the evidence and degree of anisotropy in the upper mantle.

A study of short-period (0.2 to 2.0 sec.) Rayleigh wave dispersion in signals from quarry and strip mine blasts

and small local earthquakes has shown the sensitivity of Rayleigh waves of this period range to changes in the sedimentary section. This suggests their use as a tool in shallow crustal reconnaissance.

Group and phase velocities along 57 paths from central America to central U.S. were also used, applying established methods of interpretation, in determining differences in structure between the western and eastern Gulf of Mexico and the Caribbean Sea.

### 1.3 Reduction of Ground Motion to Motion in Incident Wave.

Any study of body wave amplitudes which is concerned with the source mechanism or the velocity structure of the earth's interior must take account of the amplitude and phase distortion caused by crustal layering and the free surface at the recording site, as well as that caused by the seismograph. A knowledge of the response characteristics of the seismograph is sufficient to compensate for the latter, i.e., to reduce the trace motion on the seismogram to ground motion at the recording site. The other aspect of the problem, to relate ground motion to earth motion beneath the crust near the recording site, has occupied much of our attention.

1.31 P Waves. The relation of the ground motion to the P wave particle motion beneath the seismograph station has attracted the attention of many renowned seismologists, such as Galitzin, Byerly and his students, Gutenberg, and Hodgson. The reasons for their interest in this relationship were

quite different, and include such basic problems in seismology as the detection and location of second-order velocity discontinuities in the earth's mantle, the calculation of extended distances in source mechanism studies, the station correction for magnitude studies, and the effect of unconsolidated materials on earthquake intensity and possible structural damage. To these may be added a problem which has received much attention in the VELA-Uniform program, to determine station sites which have a large signal-to-noise ratio for the P wave and to determine how this ratio changes at an individual location with epicentral distance and azimuth.

One result of the research undertaken in this contract was to verify experimentally Haskell's conclusions, based on a theoretical study, that the P-wave ground motion depends on the crustal layering at the seismograph station. This was accomplished by calculating the apparent angle of incidence of the P wave at the seismograph stations of our network for teleseismic events. In addition, the dominant period of the first half-cycle of the P wave ground motion was measured, in order to determine the frequency dependence of the relationship between the apparent angle of incidence and the epicentral distance. The observational data compared well with values calculated from Haskell's paper, and demonstrated the necessity of including the frequency-dependence in such studies. In addition, the study explained

the earlier and seemingly paradoxical observations of Mei and Fyerly, and of Nuttli and Whitmore, that in order to satisfy the short-period data with a half-space model of the earth it was necessary to assume a velocity of about 8 km/sec., whereas Papazachos required a velocity of 6.4 km/sec. to satisfy P-wave data with periods of 7 to 15 seconds. Thus, both Haskell's theoretical calculations and the present experimental studies put an end to the statement which appeared so often in the seismological literature, to the point of almost being axiomatic, that the effective half-space velocity for the short-period waves is that of the upper-crustal layers whereas that for the long-period waves is the upper-mantle velocity.

Hannon extended Haskell's work by considering more complex crustal models. He selected models which demonstrated the effect of changes in crustal thickness, the presence of a low-velocity layer of variable thickness, such as alluvium, at the outer surface, and the presence of a low-velocity layer in the interior of the crust. Several important conclusions follow from this study. These are:

- 1) The presence of a low-velocity material at the surface causes the ground motion to be amplified. Thus one can expect a P-wave signal to have a greater amplitude at a recording site set up on lower-velocity sedimentary rocks than at one on higher-velocity igneous rocks.
- 2) The transmission coefficients for P waves with periods greater than

about one second principally depend on the total crustal thickness, the average velocity of the crustal layers, and the contrast between the upper mantle and the average crustal velocity. Thus, in doing the inverse problem of determining a crustal model from the amplitude spectrum of the observed ground motion, it is only possible to determine gross crustal properties, such as thickness and average velocity, and not the fine structure, such as the differentiation between velocity gradients and velocity discontinuities, unless one uses frequencies of one-half cycle per second and higher. 3) The presence of an internal low-velocity layer in the crust has an effect on the transmission coefficients only in the higher-frequency range.

Studies of the ratio of the amplitude of the PP and P wave ground motion, which are an extension of earlier work of Gutenberg and Richter, indicate no essential difference in the crustal structure of the Atlantic and Pacific Oceans. Both the amplitude ratios and the existence of two separate PP waves, one reflected from the base of the crust and the other from the free surface, are useful in identifying a region at which the reflections take place as being continental in character, as opposed to oceanic.

Long-period P-wave ground motion (periods of 6 or 7 seconds and greater) from teleseisms has been found to be essentially the same, both in amplitude and in wave form, for all stations of our central United States network for a



given earthquake. This indicates that the crustal structure is almost uniform throughout this area, and also that the sedimentary layers, which vary considerably in thickness and in rock type, have no discernible effect on the long-period P-wave ground motion.

1.32 S Waves. Studies of the amplitude and phase relationship of the components of the S-wave ground motion were pursued for two purposes. The first concerns the S-wave polarization angle, which has been used with much success in source mechanism studies. The second relates to the velocity-depth variation of S in the upper mantle, insofar as it affects the amplitude and travel time of S.

Our observational studies of the S-wave ground motion showed that this ground motion was linear for epicentral distances larger than about forty to forty-five degrees, and elliptical and quite complicated for lesser distances. It is important to fix the distance at which the ground motion changes from non-linear to linear, for it is only at the greater distances that the polarization angle of the S wave is approximately equal to the angle between the direction of the horizontal component of the S-wave ground motion and the great-circle path at the seismograph station.

Haskell's theoretical work, which considered the influence of crustal layering at the seismograph station, showed that the above-mentioned observations agreed with his calculated values for a continental-crust earth model.

He also noted that the amplitude and/or phase of the SV-component of the ground motion varied rapidly with wave frequency and angle of incidence at the lesser epicentral distances. Although this would indicate that the polarization angle cannot be obtained from seismograms at distances less than forty-five degrees, his analysis suggested a method which enabled us to solve the problem. By a slight extension of Haskell's calculations, we have been able to construct a set of charts that permit one to obtain the polarization angle from the ground motion for distances as small as twenty degrees. Stauder and Bollinger, in their study of the source mechanisms of the large-magnitude earthquakes of 1962 and 1963, conclude that polarization angles calculated by using these charts for distances less than forty-five degrees are in conformity with polarization angles at the larger distances which were obtained in the conventional manner.

The study of amplitude variations and travel times of S-waves which have traveled a large part of their path in the upper mantle is difficult, because these waves arrive at the epicentral distances for which the S-wave ground motion is extremely complicated. A method of determining the onset time of S has been developed, and is presently being applied to the data obtained at the LRSM stations for about eight earthquakes.



Early in the VELA-Uniform program a suggestion was made that amplitude ratios such as  $P/SH$  or  $SV/SH$  could provide a diagnostic tool for distinguishing between explosions and earthquakes, because it was expected that explosions would produce little SH motion. Even if this premise were true, one cannot apply the method without reducing the ground motion to particle motion within the earth. For example, the crustal layers and the free surface of the earth have such a large effect upon the S-wave motion that a wave whose particle motion is almost exclusively SV beneath the crust at the station can produce a ground motion which is almost completely SH in character. The conclusion which follows is that ratios of  $P/SH$  or  $SV/SH$  of the ground motion, i.e. motion corrected for the instrument response characteristics but not for the crustal layering effects, are of little value and may even be misleading when used as diagnostic techniques to classify an event as an explosion or an earthquake.

1.4 Focal Mechanism Studies. Our focal mechanism studies have progressed by the application of the theory of point sources to the interpretation of observational data of the P and S waves from teleseisms. Work originally begun under Contract AF 19(604)-8054 has been incorporated into this effort. We have also examined groups of fault plane solutions by many authors for earthquakes around the borders of the Pacific Ocean.

We have demonstrated that S wave polarization information can be used as a powerful tool in the determination of focal mechanisms. While S wave data, in our opinion, are most advantageously used as an adjunct to the P wave first motion technique, we have also developed separate methods, using S wave data alone. A computer program has been developed to this end, and has been used effectively in studying a number of earthquakes.

Certain radiation patterns of P and S waves have been found to be characteristic of a given earthquake sequence or of earthquakes in a given region. Of particular interest to detection problems, the occurrence of compressional first motion of P waves for earthquakes as recorded in the third zone, together with SV polarization of the S waves, is not a rare occurrence. Earthquakes of the Kamchatka area in particular are commonly of this nature.

The limitations inherent in methods of focal mechanism determination from the data of body waves have been examined. Chief among these are the limitation in geographic distribution of stations and the small dimensions of the seismic window on the focal sphere through which it is possible to see the earthquake focus from data of body waves recorded at  $P_n$  distances and greater.

Examination of multiple solutions, i.e., by several different authors for one and the same earthquake, as also a comparison of groups of fault plane solutions for a given

region evidence poor agreement and systematic differences in solutions by different authors. This evidence requires that caution should be exercised in drawing conclusions from the existing accumulation of published fault plane solutions.

Progress has been made in the use of S wave polarization data for smaller earthquakes at shorter epicentral distances. Use of phase equalization of surface waves was attempted for a magnitude 5 earthquake of southeast Missouri but the results were not conclusive.

1.5 Focal Depth. Two approaches have been tried to the focal depth problem.

By taking advantage of a known surface event, the BILLIKEN shot of June 28, 1963, the Pg-Pn vs Sg-Pg method was applied to two magnitude 5 earthquakes of southeast Missouri. An earthquake of 2 February 1962 was found to have a shallow focal depth; one of 3 March 1963 to have a focus deep in the crust. It was also noted that the seismogram of the latter carried considerably more power in higher frequency portion of the record than did the former.

Secondly, applying to body wave generation a source-crust model set up by Harkrider for surface waves, we have obtained the transfer function for a source in a layered system overlying a half-space as a function of source depth. It is found that for an explosive point source located at shallow depths the source-crust system acts as a rejection filter for the low frequency portion of the spectra of body waves. This conclusion seems to point to a most promising

technique of focal depth determination and indicates the advisability of further work.

1.6 Inversion of Body Wave Spectra. Two studies have contributed to the problem of inferring crustal structures under a recording site from the spectra of P waves recorded at the site.

In a preparatory study Hannon (Technical Report 3, AFCL 64-614) investigated the transfer function of a layered crust and examined the effect of varying the parameters of the crust model. He obtained synthetic seismograms for P waves recorded at the surface of various crustal models. He remarked the differences of the seismograms, but did not undertake the inverse problem.

Following the lead of Hannon, Fernandez investigated the possibility of a least squares inversion whereby a crustal model might be fitted to observed spectra of P waves. He found the partial derivatives with respect to velocity, layer thickness, etc., of the transfer function, when expressed as a function of frequency, to be so large and to vary so erratically as to make an inversion program not feasible. By expressing the transfer function in terms of a dimensionless parameter, however, a much more regular behavior was obtained. While he did not develop a least squares inversion program, Fernandez has calculated a set of master curves for the transfer functions of one and two-layer crusts. By overlaying observed spectra (or the ratio

TW/TU of the spectrum of the vertical component to that of the horizontal) on the master curves, a best fitting crust is found by a curve-matching technique. Using long-period records of the Saint Louis University net, the technique is remarkably successful in determining the average features of the crust. The method indicates that in the central U.S. the average crustal velocity is 6.6 km/sec and the crustal thickness is 42 km. Finer details of crustal structure may be determinable using the shorter period portion of the body wave spectra. This material is being submitted to AFCRL as Scientific Report Number 13.

#### 1.7 Effect of Low-Velocity Channel on Travel Times of Body Waves.

From the pioneering work of Gutenberg and others it is well-known that low-velocity channels in the earth can produce shadow zones. The best example of this is the shadow zone for the P wave resulting from the earth's core. There is both observational evidence and geometrical proof obtained by constructing ray paths that the existence of a region in the earth for which  $r/v$  increases with depth can produce a shadow zone if the hypocenter is located in or above the low-velocity channel. But too little attention had been given to the converse problem, i.e., does the presence of a low-velocity channel always produce a shadow zone. A survey of the literature suggested that, except for the work of Lehmann and Nishimura, the converse was generally accepted as being true.

The problem does not allow a simple analytical solution, because the expressions for the travel time and epicentral distance of a ray traveling through a earth model which traverses a region in which  $r/v$  increases with depth involve non-convergent integrals. But from purely physical reasoning we can argue that there must be a solution, because the rays encountering such a low-velocity channel do arrive at the earth's surface in a finite amount of time. The method we used to solve this problem employed ray tracking which was programmed for a digital computer.

A systematic study was made of the various parameters of the low-velocity channel which can affect the time-distance curve. The most significant result was that a sufficiently large velocity gradient (increase of velocity with depth) will not only produce no shadow zone, but will give an overlapping of the segments of the curve so that it is possible to have three wave arrivals at a given distance, a result which is qualitatively similar to that produced by an earth model with no low-velocity channel but rather an abrupt increase in the velocity or velocity gradient with depth.

Attention was also given to the inverse problem, namely to determine the velocity-depth relation from P-wave travel times. The data used were the P times in North America from the nuclear events BILBY and GNOME. Although there is some ambiguity in the details of the velocity-depth relation obtained in this manner, it can definitely be stated that



there are lateral variations in the upper-mantle P-wave velocities. The central and eastern parts of the United States have in general higher Pn velocities than the western part. There is no strong evidence for the existence of a low-velocity channel for P in the central and eastern United States. If one exists it is relatively deep, not very thick, and entails only a small velocity decrease. The upper-mantle P-wave velocity structure in the western United States, however, is more complex and suggests large lateral variations. The low-velocity channel for P is shallower and more pronounced, and can produce shadow zones for P such as those postulated by Gutenberg for southern California.

#### 1.8 Local Crustal Structure, Seismicity, Pn Velocity. Several different studies fall under this heading.

A continuing study of the seismicity of the southeast Missouri area has led to new understanding of this main seismic region. Normally about one 4.5-5.0 magnitude earthquake occurs each year in this region. About four other shocks large enough to be felt occur each year. Study of these earthquakes has yielded more reliable regional travel time curves. Investigation of the region is hampered, however, by lack of seismic stations in the immediate epicentral region. More recently two temporary long-recording, trailer installed stations have been set up at epicentral distances of the order of 60 km and less. While in the past larger earthquakes have occurred with apparently no aftershock

sequence, we have observed at least one aftershock series following upon two magnitude 4 earthquakes of 25 May 1964. We also find that the level of seismic activity includes an average of one small earthquake per week. By placing untended stations in boreholes in the immediate epicentral region we feel we can for the first time obtain reliable information on focal depths.

Following a suggestion made by Stanford Research Institute, after an unsuccessful attempt to monitor aftershocks of the southeast Missouri earthquake of 3 March 1963, ARPA sponsored a calibration shot in the area to check accuracy of the epicenter location and to test the calibration procedure. Accuracy of the epicenter location was convincingly checked; the calibration shot, code named BILLIKEN, was located within 2-3 km of the shot point using conventional procedures for locating earthquake epicenters in the region. The calibration shot has been of value in subsequent epicenter locations and has also been helpful in obtaining some measure of focal depth for the earthquakes of 2 February 1962 and 3 March 1963.

A joint U.S. Geological Survey - Saint Louis University explosion refraction survey was conducted along two lines in Missouri in June 1963. The reduced travel-time plot shows arrivals to be better fitted by a continuously changing curve rather than by a small number of straight line segments. Accordingly, interpretation of the data has proceeded using



crustal models characterized by continuous, increasing velocity-depth functions. Two computer programs have been developed: one which calculates travel-time curves and amplitudes for a given velocity-depth function; a second (more interesting) which does the inverse problem - it calculates the velocity depth function from a given travel time curve. This work is unpublished as yet, but is nearing completion.

## 2. Abstracts

### 2.1 Network of Seismic Stations.

#### THE RESPONSE CHARACTERISTICS OF THE LONG PERIOD SEISMO- GRAPHS OF THE SAINT LOUIS UNIVERSITY NETWORK.

Otto Nuttli and Thomas V. McEvilly. Earthquake Notes,  
Vol. XXXII, Sept.-Dec. 1961, 27-36.

Abstract: Saint Louis University, under a VELA-Uniform contract, has set up a quadrilateral network of permanent seismograph stations in the central United States. These stations are operated with the cooperation of the University of Indiana at Bloomington, the University of Missouri at Rolla, Kansas State University at Manhattan, and Loras College at Dubuque, Iowa. The latitude and longitude of the stations are given in Table II of the text.

The purpose of this paper is to give a description of the long-period seismographs operating at these stations. Because the seismographs are intended to provide data for both the study of focal mechanisms using S waves and the phase and group velocity of long-period surface waves, the seismograph systems were designed so as to give a nearly constant magnification for periods of about two to fifty seconds, a smoothly and slowly changing instrumental phase shift with increasing period of the earth motion, and stability of operation. The system adopted uses a long-period Sprengnether seismometer operating with a natural period of fifteen seconds, with the output of the two coils connected in series. Shunt and attenuator resistances of three hundred ohms each give a loose coupling between the seismometer and ninety-second galvanometer. The system has a magnification of about one thousand from two to fifty seconds, and of one hundred at a period of approximately two hundred seconds.

Magnification and velocity sensitivity curves are given for the three components of the long-period instruments at each of the four stations. In addition, phase and group delay correction curves are given for one of the seismographs.

## 2.2 Phase and Group Velocity Studies.

### CENTRAL U.S. CRUST-UPPER MANTLE STRUCTURE FROM LOVE AND RAYLEIGH WAVE PHASE VELOCITY INVERSION.

T. V. McEvilly, Bull. Seism. Soc. Am., 54: 1997-2015.

Abstract: Fundamental mode Rayleigh and Love wave phase velocities in the period range 5 to 80 seconds have been measured in the central U.S. Using the concept of constant partial derivatives of phase velocity with respect to layer parameters in a least-squares inversion scheme a structural model for the area was determined. Several parameters were constrained on the basis of other available data. It was not possible to fit satisfactorily both Rayleigh and Love data with a simple isotropic model. Conclusions require either anisotropy in the upper mantle or systematic errors in the phase velocity measurements.

### EFFECT OF SEDIMENTARY THICKNESS ON SHORT-PERIOD RAYLEIGH WAVE DISPERSION.

T. V. McEvilly and William Stauder, S.J., Geophys., 30, 198-203.

Abstract: Large differences in group velocities of short-period Rayleigh waves from stripmine blasts for different propagation paths in the Ozark Uplift-Illinois Basin area have been observed. Good well control in the area makes possible the construction of structural models of the sediments-basement system for these paths. Theoretical group velocities computed for these models agree well with observations, thus explaining the large variations in velocities in terms of basement-depth differences. This sensitivity of short-period surface waves to sedimentary thickness suggests an inexpensive, single-station technique of basin reconnaissance where commercial blasting is available.

### DISPERSION OF RAYLEIGH WAVES IN THE GULF OF MEXICO AND CARIBBEAN SEA.

Basil C. Papazachos, Bull. Seism. Soc. Am., 54: 909-925.

Abstract: Group and phase velocities of Rayleigh waves along 57 paths between Central America and the central United States were determined. The waves examined were of period between 15 and 60 seconds and crossed the Gulf of Mexico and Caribbean Sea in many directions. The following conclusions about the structure of the region are drawn:

Along the paths crossing the western and central Gulf and the regions near the coast of Texas and the eastern

coast of Mexico the velocities were found to be very low. This is attributed to the great thickness of the sediments in these regions.

The velocities along paths crossing the eastern Gulf and westernmost Caribbean were found to be higher than the typical continental velocities. This is considered as an indication of a difference in structure between the eastern and western Gulf of Mexico. Along one path in the western Caribbean Sea between Colombia and Cuba the velocities were almost continental. High velocities found for part of the eastern Caribbean indicate an almost oceanic character for this region.

For each earthquake examined the initial phases were determined with an error less than  $+\pi/4$ . For a given earthquake in all cases except two the initial phases were found to be the same at all stations.

## 2.3 Reduction of Ground Motion to Motion in Incident Wave.

### 2.31 P Waves.

SOME OBSERVATIONS RELATING TO THE EFFECT OF THE CRUST ON LONG-PERIOD P-WAVE MOTION.

Otto Nuttli, Bull. Seism. Soc. Am., 54: 141-149.

Abstract: Long-period P waves recorded in the central United States at distances of 20 to 110 degrees for earthquakes of magnitude 6 and greater indicate that the amplitude of the ground motion is very similar at all stations in the area. The crust is uniform in this region, but the sedimentary section varies both in thickness and in character. Direction of approach, as determined by the ratio of the amplitudes of the horizontal components of motion, does not differ significantly from the great-circle path in the majority of cases studied.

Apparent angles of incidence cannot be satisfactorily explained by a half-space model, because calculations based on such a model require a larger value of the P-wave velocity for the shorter period waves. However, calculations based upon Haskell's model of a crustal layer over a half-space give a satisfactory fit to the observed data.



# SOME EFFECTS OF THE CRUST AND FREE SURFACE ON THE AMPLITUDES OF BODY WAVES.

Otto Nuttli, VESIAC Conf. on Variations of the Earth's Crust and Upper Mantle, July 1964.

Abstract: Both theoretical and observational studies have demonstrated that the motion recorded by a seismograph, after reduction for the response characteristics of the instrument, does not correspond to the motion of a body wave just before it strikes the earth's surface. This paper concerns the effects of the crust and free surface on data used in magnitude and focal mechanism studies, and the applications of such effects to the determination of the crustal structure at the recording site.

The principal conclusions are:

(a) The crustal and upper-mantle structure has an important effect on the amplitude and wave shape of recorded body-wave motion. However, these effects depend not only on the crustal structure, but also upon the frequency content of the incident signal and the epicentral distance.

(b) A consideration of the effects of the crust on the amplitudes of the recorded P-wave motion may help to reconcile differences observed between magnitudes (m) determined from short-period waves and those from long-period waves.

(c) It is necessary to consider the effect of crustal structure when determining the polarization angle of shear waves for epicentral distances less than about 5500 to 6000 km.

(d) It is possible, at least in theory, to use observations of recorded body-wave motion to infer crust and upper-mantle structure. In order to obtain a high resolving power, it will probably be necessary to work with frequencies greater than 5 cps. However, if one is primarily interested in total crustal thickness and average properties, lower-frequency waves (periods on the order of ten seconds) may be used. The latter frequency range has the advantage of necessitating fewer arithmetical calculations.

## ANGLE OF INCIDENCE AND AMPLITUDE RATIO OF P AND PP WAVES.

Basil Papazachos. Bull. Seism. Soc. Am., 54: 105-121.

Abstract: Apparent angles of incidence and amplitudes of P and PP waves of period 7 to 15 seconds were obtained from seismograms of the long period Columbia-Sprengnether instruments at the stations Manhattan (Kansas), Rolla (Missouri), Dubuque (Iowa) and Bloomington (Indiana). The calculated

angle of incidence, by assuming Poisson's ratio equal to  $\frac{1}{4}$ , agrees with a velocity of 6.4 km/sec for these longitudinal waves near the surface of the earth. The amplitude ratios of reflected to incident waves at the points half the distance between epicenters and stations were calculated. Comparison of these ratios with theoretical results shows that the unsymmetrical radiation at foci and errors in measurements make difficult, but not impossible, the use of these ratios for studying the structure of the earth. Another possible way to use the relative amplitudes of P and PP waves for studying regions of doubtful structure is to examine if those regions give reflections not only at the surface of the earth but also at the bottom of a possible crustal layer. Atlantic reflections indicate that these longitudinal waves are not affected by any surface crustal layer under the Atlantic Ocean.

#### AN APPLICATION OF THE HASKELL-THOMSON MATRIX METHOD TO THE SYNTHESIS OF THE SURFACE MOTION DUE TO DILATATIONAL WAVES.

W. J. Hannon, Bull. Seism. Soc. Am., 54: 2067-2080.

Abstract: The surface motion arising from a plane dilatational wave striking the base of a layered system is obtained by Fourier synthesis using the frequency dependent transmission coefficients which may be computed by the Haskell-Thomson matrix method. Theoretical seismograms illustrating the effect of thin, low-velocity surface layers on the surface motion are constructed from the transmission coefficients of four crustal models.

#### 2.32 S Waves

##### ON THE DETERMINATION OF THE POLARIZATION ANGLE OF THE S WAVE.

Otto Nuttli and John D. Whitmore, Bull. Seism. Soc. Am., 52: 95-107.

Abstract: This study is concerned with determining the minimum epicentral distance for which it is permissible to obtain the value of the polarization angle of the S wave by measuring the angle between the great circle path at the station and the direction of the horizontal component of the S wave particle motion obtained from the seismograms. This critical distance can be determined by the fact that at smaller distances the particle motion of the earth's surface due to the incidence of S will be nonlinear (the SH and the horizontal and vertical components of SV will be out of phase with respect to one another) while at larger

distances the particle motion will be linear. An analysis of the S motion recorded by the Galitzin-Wilip seismographs at Florissant indicates that the critical distance is 42 degrees. The periods of these S waves are of the order of 10 second. The analysis also shows that the effective P wave velocity of teleseismic waves at the earth's free surface is 7.74 km/sec, and the effective value of Poisson's ratio and the effective S wave velocity at the earth's surface are 0.25 and 4.46 km/sec, respectively. By effective values are meant the values of the velocities and Poisson's ratio that govern the angle of incidence of the waves at the earth's surface.

#### THE DETERMINATION OF S-WAVE POLARIZATION ANGLES FOR AN EARTH MODEL WITH CRUSTAL LAYERING.

Otto Nuttli, Bull. Seism. Soc. Am., 54: 1429-1440.

Abstract: This paper presents a method for determining the polarization angle of S waves which takes account of the crustal layering at the seismograph station. Charts are given for four crustal models, corresponding to normal continental, thick, and thin crusts, which enable one to obtain the polarization angle at the top of the mantle beneath the seismograph station.

The equations to be used for obtaining the polarization angle are

$$\begin{aligned}\tan \epsilon &= F_h \tan \gamma \\ \tan \epsilon &= F_v \tan \delta\end{aligned}$$

where  $\epsilon$  is the polarization angle,  $\gamma$  is the angle between the horizontal component of the S-wave surface motion and the great circle path at the station,  $\delta$  is the angle between the vertical axis and the component of the S-wave surface motion in the plane transverse to the great circle path, and  $F_h$  and  $F_v$  are functions of wave period, epicentral distance, and the crustal structure at the seismograph station. Values of  $F_h$  and  $F_v$  for four crustal models are given in the paper.

#### A METHOD FOR DETERMINING THE TIME OF ONSET OF S WAVES OF SHALLOW EARTHQUAKES AT INTERMEDIATE DISTANCES.

Otto Nuttli and Abou-Bakr Ibrahim, Paper presented at the Annual Meeting of the Seismological Society of America, Seattle, Washington, March 28-30, 1964.

Abstract: Observational data concerning the travel times

of S waves from shallow earthquakes at distances of about 2000 to 4000 kilometers are very limited, owing to the difficulty in identifying the beginning of the S-wave motion. Both interfering longitudinal waves and phase shifts in S due to crustal layering and the earth's free surface obscure the onset of the S arrival. However, a comparison of observed with theoretical particle motion diagrams enables one to determine the beginning of S in cases where it is difficult to do so from a visual inspection of the seismograms. Examples of the application of this method, including theoretical particle motion diagrams for an earth model with crustal layering, are presented.

#### 2.4 Focal Mechanism Studies.

##### SOME P AND S WAVE STUDIES OF THE MECHANISM OF EARTHQUAKES AND SMALL CHEMICAL EXPLOSIONS.

William Stauder, S.J., and Carl Kisslinger, VESIAC Spec. Rpt. Proceedings of the Colloquium on Detection of Underground Nuclear Explosions, August 1962, pp.125-140.

Abstract: Both the earthquake and explosion studies point up the need for further research into the nature of seismic source mechanisms as such. They show that careful observations of S waves are a useful tool in this type of investigation and that the S waves are diagnostic of the physical processes taking place at the source.

As yet, no difference in the S waves from the two types of sources has been discovered that will indicate which source is operative. The presence or absence of S waves is certainly not a criterion. The ratio of S to P or of Rayleigh to Love may be indicative, but much research remains to be done in this area. Moreover, such studies must not ignore the effect of the medium surrounding the explosion on the amplitude of S waves relative to P.

Unfortunately, data from nuclear explosions are available for a limited variety of media. We suggest that future underground nuclear explosions be given the most complete azimuthal coverage practical and that this coverage be with three component instruments. In addition, careful pre- and postshot surveys of cracks and the relation of these to regional joint patterns should be included.



S-WAVE STUDIES OF EARTHQUAKES OF THE NORTH PACIFIC, Part I:  
KAMCHATKA

William Stauder, S.J., Bull. Seism. Soc. Am., 52, No. 3,  
527-550.

**Abstract:** The polarization of S waves at stations distributed azimuthally about the source is examined for each of twenty-three Kamchatka earthquakes of 1950-1960. In nineteen of these earthquakes the P and S wave data are in agreement with a double couple source as the point model of the focal mechanism. The S waves indicate a uniform mechanism which repeats itself from earthquake to earthquake and from which it may be inferred that the axes of greatest and least stress at the foci tend to lie in a vertical plane normal to the trend of the Kamchatka-Kuriles arc. The axis of least stress usually plunges almost vertically under the continent, but may also plunge less steeply, at angles as low as 45 degrees. At least two earthquakes may be represented by a single couple source.

S-WAVE STUDIES OF EARTHQUAKES OF THE NORTH PACIFIC, PART II:  
ALEUTIAN ISLANDS.

William Stauder, S.J., and Agustin Udias, S.J., Bull. Seism. Soc. Am., 53: 59-77.

**Abstract:** The polarization of the S wave at stations distributed azimuthally about the source is examined for each of twenty-five Aleutian Island earthquakes. A combination of data from the first motion of P and from the polarization of S is then used to study the focal mechanisms of the earthquakes. This combination of P and S wave data is found to make possible a good determination of the focal mechanism in cases where data from the first motion of P alone do not suffice.

The earthquakes are divided into three groups according to three basic patterns of S wave polarization. The first group (fourteen earthquakes) corresponds to a double couple. The second group (five earthquakes) and the third group (six earthquakes) are conformable to conjugate shears and may therefore be explained by single couple sources of opposite moment, respectively. It is shown that a uniform principal stress system predominates in the region and that the axis of greatest compressive stress is normal to the trend of the island arc.

# A LEAST SQUARES METHOD FOR EARTHQUAKE MECHANISM DETERMINATION USING S-WAVE DATA.

Agustin Udias, S.J., Bull. Seism. Soc. Am., 54, 2037-2047.

Abstract: In this paper a numerical approach to the determination of focal mechanisms based on the observation of the polarization of the S wave at N stations is presented. Least-square methods are developed for the determination of the orientation of the single and double couple sources. The methods allow a statistical evaluation of the data and of the accuracy of the solutions.

## APPLICATION OF NUMERICAL METHOD FOR S-WAVE FOCAL MECHANISM DETERMINATIONS TO EARTHQUAKES OF KAMCHATKA-KURILE ISLANDS REGION.

Agustin Udias, S.J., and William Stauder, S.J., Bull. Seism. Soc. Am., 54, 2049-2065.

Abstract: The least squares method for the determination of focal mechanism using S-wave data developed by Udias (1964) has been applied to 34 earthquakes of the Kamchatka-Kurile Islands Regions. For most of the earthquakes studied the source mechanism was found to conform best to a double couple model. The accuracy and stability of the solutions show a steeply dipping axis of tension and an almost horizontal axis of pressure. The orientation of the pressure axes is normal to the regional trend. The direction of the stresses suggest a thrust faulting with predominantly dip slip motions such that the continental block moves over the oceanic.

## GEOMETRICAL PROPERTIES OF GROUPS OF FAULT PLANE SOLUTIONS

Allan Cox and William Stauder, S.J., Bull. Seism. Soc. Am., 54: 87-104.

Abstract: A formal method of analysis is proposed whereby groups of first motion solutions may be examined for evidence of regional patterns of symmetry, abstracting from any particular model of the focus or from assumptions about regional tectonics. Axial, planar, and conical symmetry are discussed with special consideration being given to the constraints placed on the spacial distribution of axes by the geometry of sets of orthogonal axes. Examples from the literature are given of axial and planar symmetry, and it is shown that in some instances attention to the geometry of the axis system suggests modifications in the interpretation of regional patterns. Analytical aids are also

given to associate the use of eigenvalues with the graphical methods in discerning the type of symmetry and indicating the degree of scatter, and a method is described for calculating statistical confidence limits for the case of axial symmetry.

#### A COMPARISON OF MULTIPLE SOLUTIONS OF FOCAL MECHANISMS.

William Stauder, S.J., Bull. Seism. Soc. Am., 54, 927-937.

Abstract: The occurrence of focal mechanism solutions of the same earthquake by different authors is examined. Of 42 instances of such multiple solutions for earthquakes which occurred around the borders of the Pacific Ocean, it is found that of 84 possible pairs of multiple solutions agreement is excellent in 8 cases, good in 13, fair in 19, poor in 19, and no agreement in 25. The implication for focal mechanism studies is illustrated by examining the focal mechanism solutions of deep-focus earthquakes under the Sea of Japan.

#### THE FOCAL MECHANISM OF TWO PERUVIAN EARTHQUAKES.

Daniel E. Ochoa and William Stauder, S.J., Pure & Applied Geophysics, 58 (1964/II): 114-122.

Abstract: The focal mechanisms of two Peruvian earthquakes, January 15, 1958, and January 13, 1960, are determined using data from both the first motion of P and the polarization of S. The fault motions correspond to strike slip motion on neighboring faults corresponding in strike to geophysical evidences of regional faulting. The motion is left lateral in one of the shocks, right lateral in the other.

#### THE PRESENT STATUS OF FAULT PLANE SOLUTIONS FROM P AND S WAVES AND THE RELATION OF THESE SOLUTIONS TO TECTONIC STRESS FIELD.

William Stauder, S.J. Proceedings VESIAC Conference on Focal Mechanisms, LaJolla, March 1965, (in press) University of Michigan.

Abstract: The P wave first motion method of focal mechanism determination is used to infer the symmetry of a seismic source. In general, three classes of solutions may be distinguished: those in which two P nodal planes are clearly determined, those in which only one nodal plane

is clearly determined, those in which neither nodal plane is distinguished, i.e., all available first motion readings are of the same sign. Even in the latter case, while the plane of faulting or direction of motion cannot be discerned, considerable information about the stress field at the source of the shock is indicated; for instance, if all first motion readings are compressional, the axis of least principal stress is steeply inclined.

Inability to determine both nodal planes in all cases results from a limitation inherent to the method, that is, rays leaving the source and arriving at stations at Pn distances or greater all leave the focus downward through a narrow cone which represents  $1/4$  or less of the area of the focal sphere. A related limitation arises from the geographic distribution of seismic stations. These and other limitations emphasize the desirability of using S wave data and surface wave data in focal mechanism determination. Methods of S wave analysis and surface wave analysis have, in fact, been developed and have been used successfully in focal mechanism studies. These methods have greatly enhanced the reliability of fault plane solutions.

In examining groups of fault plane solutions, considerable evidence of bias in the solutions, of unreliability of individual solutions, and of systematic differences in solutions by different authors indicate that caution should be exercised in undertaking statistical studies of all the fault plane solutions for a given region. Nevertheless, where good solutions are available, consistent relations between solutions are discerned. Most notably, around the borders of the North Pacific the axes of greatest and least stress seem to lie in a steeply dipping plane normal to the trend of the geographic features. The axis of compressive stress tends to be inclined by an angle of  $10^\circ$  to  $30^\circ$  to the horizontal.

#### THE DIRECTION OF CRUSTAL MOVEMENTS INDICATED BY EARTHQUAKE DATA

William Stauder, S.J. Paper delivered at the Research Symposium, Annual Meeting of the AAPG-SEPM, New Orleans, April 26-29, 1965.

Abstract: Two types of seismic data give evidence of the direction of crustal movements: the spatial and temporal sequence of earthquake hypocenters and the focal mechanism determinations of individual earthquakes or of groups of earthquakes. Examples illustrate the power of the methods of focal mechanism determination from P and S waves,



as also the limitations inherent to the methods. Further, examination of groups of published fault plane solutions shows evidence that many of these solutions are not reliable. A critical examination of the reliability of individual fault plane solutions before these are used as the bases of regional statistical tectonic studies.

Conclusion of tectonic significance from the data of earthquakes include the following. First, the predominance of strike slip faulting, once reported as a conclusion of focal mechanism studies, is no longer apparent from the data of fault plane solutions. Second, around the borders of the northern and western Pacific Ocean the predominant horizontal stress is a compression normal to the trend of the tectonic features. Third, there is a radical difference between the earthquake zones of the circum-Pacific or Alpine belt, and those of the mid-oceanic rifts; the latter represent very narrow zones of seismic activity in which the seismic evidence, as yet incomplete, indicates that the rift is indeed a tensional feature. Fourth, that along the world rift system concentrations of epicenters are associated with offsets of the oceanic ridges. These offsets, in turn, correspond to the intersection of the ridge by east-west trending fracture zones. Along the fracture zones themselves the current seismic activity is limited to the region of offset. These relations have been especially investigated by Sykes. Fifth, Sykes has also shown that in the island arc structure of the Kermadec-Tonga Islands, earthquake hypocenters lie along a plane dipping inward below the island arc, and that at all levels the hypocenters reflect the surface details of the arc. Evidence from the focal mechanism solutions of earthquakes occurring along the arc suggest that the planes of faulting follow this same pattern.

## 2.5 Focal Depth

THE TRANSFER FUNCTION FOR P-WAVES FOR A SYSTEM CONSISTING OF A POINT SOURCE IN A LAYERED MEDIUM.

Karl Fuchs, Scientific Report No. 12 prepared under Contract AF 19(604)-7399 of Air Force Cambridge Research Laboratories for ARPA Project VELA-Uniform, AFRL-65-526.

Abstract: This paper investigates in what manner the spectrum of body waves radiating from point sources in a multilayered medium over a homogeneous half-space is different from the spectrum of body waves from the same source in an infinite medium. The effect of the system consisting

of a point source in a layered crust on the spectrum of p-waves observed at large distances in the half space is studied. Analytical expressions for the transfer function of this system are derived for three types of point sources: an explosive source, a single couple, and a double couple of arbitrary orientation within the crust.

Preliminary numerical computations for the explosive source at various depths in a realistic model of the earth's crust study the effect of: a) the angle of incidence into the homogeneous half-space, b) the source depth, c) minor variations of the crustal model. In the case of an explosive source the most influential parameter of the transfer function is the source depth. In shallow explosions the low frequency part of the spectrum of body waves is comparatively rejected.

## 2.6 Inversion of Body Wave Spectra.

### SOME EFFECTS OF A LAYERED SYSTEM ON DILATATIONAL WAVES.

Willard J. Hannon. Technical Report 3, July 1964, prepared for Air Force Cambridge Research Laboratories, OAR, under ARPA Project VELA-Uniform. AFRL Rpt. No. 64-614.

Abstract: In this report, the effect of the crustal model on the variation of the surface motion with the angle of incidence and the frequency is examined for several crustal models. The study was carried out by programming the problem for the IBM 1620 and 7072 computer systems using the matrix formulation originally suggested by Thomson and perfected by Haskell and Dorman. From these programs, the ratios of the displacements at the free surface to the total amplitude at depth were computed for several crustal models in ranges of frequency and angle of incidence of interest in seismology. These ratios are, in effect, transmission coefficients.

Six crustal models having such features as thin low-velocity surface layers, low-velocity layers at depth, and relatively thick and relatively thin total thicknesses were considered. For each model, the transmission coefficients were computed for frequencies ranging from .02 cps to 10.0 cps in steps of .02 cps, and for angles of incidence ranging from 21 degrees to 53 degrees in steps of 4 degrees. Haskell's model was included in these calculations in order to obtain a check on the calculations. A further check was obtained by using the transmission coefficients to synthesize

the surface motion due to an incident wave of the form  $(1/\pi) (\sin 20 \pi t)/t$  and comparing these values with those predicted by ray theory. The agreement was very good.

As a result of these calculations, the importance of the frequency dependent character of the crustal effect has been further emphasized. It has been shown that a thin low-velocity surface layer causes a large variation in the transmission coefficients, while a low-velocity layer at depth has little effect, especially at low frequencies. Further, it has been shown that the total crustal thickness is one of the most significant factors in determining the variation with frequency. The transmission coefficients of relatively thick crustal models have a much more rapid frequency variation than those of the relatively thin crust. At frequencies less than .2 cps, it is very difficult to distinguish between crustal models of very nearly the same thickness by means of the frequency variation of the transmission coefficients unless the internal structure is very different.

#### THE DETERMINATION OF CRUSTAL THICKNESS FROM THE SPECTRUM OF P WAVES.

Luis M. Fernandez, S.J. Scientific Report No. 13, Sept. 1965, prepared for Air Force Cambridge Research Laboratories, OAR, under Contract AF 19(604)-7399, ARPA Project VELA-Uniform.

Abstract: When the layers of the earth's crust are perturbed by compressional seismic energy they vibrate in a frequency characteristic pattern. This pattern depends not only on the frequency content of the exciting seismic energy but also on the elastic parameters and thicknesses of the layers. This dependence may be on the basis of a method to investigate the crust of the earth.

In order to obtain information independent of the source of energy the spectrum of the vertical component of motion should be divided by the spectrum of the horizontal component. This ratio represents the tangent of the apparent angle of emergence as a function of frequency and as such depends only on the angle of incidence of the ray and the system of layers below the station of observation.

The parameters of the crust may be obtained by comparison of theoretical and observed spectra. To facilitate this comparison a set of master curves was calculated using the matrices development of Haskell. Calculations of these curves are in terms of a dimensionless parameter instead of

frequency. This parameter allows the grouping of the curves corresponding to different crustal models into families of curves. A set of master curves of the apparent angle of emergence for one-layer models and for different angles of incidence and contrasts of velocities between the crust and the mantle is presented. This set is complete in the sense that all the one-layer models may be interpolated. A second set for some combinations of two-layer models is also presented. The characteristics of these curves are discussed from the point of view of periodicity and amplitude to investigate the influence of the layer parameters on their form. Constructive interference considerations and Fourier analysis of a pulse multiply reflected within the crust reveal that the amplitude of the curve fluctuations depends on the velocity contrast at the interfaces of the crust and of the crust-mantle. The periodicity of the fluctuations depends on the time lags between the first arrival of the direct P wave and the secondary arrivals of the reflections and seismic conversions. Long-period fluctuations correspond to short time lags and short-period to long time lags.

Observations of the spectrum of the apparent angle of emergence were obtained by dividing the smoothed spectra of the vertical and horizontal component seismograms. In order to avoid the influence of reflections at the crust near the source or reflections from the core of the earth the earthquakes selected were of intermediate and large focal depth.

Application of the method to the long-period seismograms of the Saint Louis University Network of stations gives an average P velocity in the crust of 6.6 Km/sec. and a total thickness of the crust of 42 Km. for the central part of the United States under these stations.

## 2.7 Effect of Low Velocity Channel on Travel Time of Body Waves

### TRAVEL-TIME CURVES FOR A LOW-VELOCITY CHANNEL IN THE UPPER MANTLE.

John Dowling and Otto Nuttli, Bull. Seism. Soc. Am., 54, 1981-1996.

Velocities within the earth can be determined from body wave time-distance (T-D) data by the Herglotz-Wiechert method provided the velocity does not decrease too rapidly with depth. Until the present time, the properties of T-D curves for rapid decreases of velocity with depth have been considered only qualitatively.



This paper presents a technique for calculating a T-D curve for any velocity distribution, including continuous and discontinuous increases and decreases of velocity with depth. Some properties of T-D curves are quantitatively studied by systematically varying the characteristics of a single model and noting the corresponding variations in the calculated T-D curves. From this it is concluded that a significant low-velocity channel may not be evidenced by a shadow zone but rather by an overlapping of two distinct branches of the T-D curve. It is further concluded that the presence of a shadow zone implies a very gentle velocity gradient below the low-velocity channel.

By fitting a calculated T-D curve to observed data one can determine velocity as a function of depth even when the velocity decreases rapidly with depth, when a low-velocity channel exists. Observed T-D data for two underground nuclear explosions (GNOME and BILBY) measured in four different azimuths were fitted with T-D curves calculated for assumed velocity distributions. It is concluded that these data can be satisfied by a low-velocity channel for P waves in the upper mantle. The character of this channel (depth, thickness and velocity) was determined in each azimuth. The depth to its top was shallow ( $70 \pm$  km) in the western U.S. and deep ( $125 \pm$  km) in the eastern U.S. The velocity gradient below the channel is sharp enough to produce no prominent shadow zones. There are significant lateral changes in upper mantle velocities in the western U.S.

## 2.8 Local Crustal Structure, Etc.

$P_n$  VELOCITY AND OTHER SEISMIC STUDIES FROM THE DATA OF RECENT SOUTHEAST MISSOURI EARTHQUAKES.

William Stauder, S.J., and Gilbert Bollinger. Bull. Seism. Soc. Am., 53: 661-679

Abstract: Five earthquakes occurred in the southeastern Missouri seismic region during the first seven months of 1962. The largest of these took place on 2 February 1962, and was located near New Madrid. The felt area of this shock covered 35,000 square miles; the maximum intensity was Intensity V in the Modified Mercalli scale. The magnitude is estimated to have been  $4\frac{1}{2}$  to  $4\frac{3}{4}$ .

$P_n$  arrival times from thirty-five stations in the distance range 200 km to 1000 km fit a composite travel time curve for all five earthquakes given by

$$t = 5.56 \pm 0.21 \text{ sec} + \Delta / (8.23 \pm 0.02 \text{ km/sec}).$$

This contrasts with interval velocities of 8.3 km/sec to 8.5 km/sec obtained by Herrin and Taggart for this region from the GNOME data.  $S_n$  and P and S crustal velocities are also studied.

Pulse-like Rayleigh and Love waves were also recorded, each indicating a group velocity maximum at a period of about 6 seconds. The amplitudes of each of these wave types vary strongly, and in an inverse relation, with azimuth about the source. Group velocities correlate with the sedimentary and upper crustal structure along the path.

#### THE SE MISSOURI EARTHQUAKE OF 3 MARCH 1963.

William Stauder, S.J., and Michael Goodwin. Earthquake Notes, 34 (Sept.-Dec. 1963): 74.

Abstract: P travel times for the earthquake of 3 March 1963 fit a least-squares travel time curve given by the relation

$$t = (6.29 \pm 0.29) \text{ sec} + \Delta / (8.24 \pm 0.03 \text{ km/sec})$$

This equation applies in the distance range 200 to 1000 km. The  $P_n$  velocity from refraction surveys and from the BILLIKEN experiment are slightly lower.

Microseismic data indicate a maximum intensity of VII. Radius of the felt area was at least 200 miles. Magnitude determinations range from 6 to 4. A preliminary discussion will be given of the depth of focus, focal mechanism, and group and phase velocities of the sedimentary branch of the Love and Rayleigh wave curves.

#### THE BILLIKIN CALIBRATION SHOT IN SOUTHEAST MISSOURI.

William Stauder, S.J., John Dowling and Wayne H. Jackson. Scientific Report 4 prepared for Air Force Cambridge Research Laboratories, OAR, under Contract AF 19(604)-7399 for ARPA Project VELA-Uniform. AFCRL 64-659.

Abstract: On June 28, 1963, a 20,000 lb. high-explosive "calibration-shot," code named BILLIKEN, was detonated near the epicenter of the magnitude 5 Southeast Missouri earthquake of March 3, 1963. The experiment was suggested by personnel of Stanford Research Institute after field units set up in the epicentral area failed to record aftershocks.

The shot was sponsored by the Advanced Research Projects Agency and conducted jointly by the Crustal Studies Branch of the U. S. Geological Survey and Saint Louis University.

Using arrival times at stations comparable to those used in locating the March 3 earthquake, the instrumental epicenter of BILLIKEN was located within 2 to 4 kilometers of the shot point. This confirms the accuracy of epicenter locations in this area from the data of near-regional stations. The shot has also permitted "calibration" of the area, making possible epicenter locations using time differences of arrivals at pairs of stations. To the east, north and west of the shot-point travel times from BILLIKEN agree with those of previous earthquake studies and of a current refractions survey; to the south negative residuals were obtained. A comparison of the ( $P_g$ - $P_n$ ) vs ( $S_g$ - $P_g$ ) time intervals from BILLIKEN with those for the earthquakes of 2 February 1962 and 3 March 1963 indicates a focal depth deep in the crust for the former, shallow for the latter.

#### APPLICATION OF CONTINUOUS VELOCITY-DEPTH FUNCTIONS TO INTERPRETATION OF CRUSTAL REFRACTION DATA IN MISSOURI.

S. W. Stewart and William Stauder, S.J. Paper presented at Seismological Society of America meeting, Seattle, Wash., March 1964.

**Abstract:** Two reversed seismic-refraction profiles, each about 300 km long, were recorded in northern and southern Missouri in June 1963, as the result of a co-operative program between the U. S. Geological Survey and St. Louis University. Shot points in northern Missouri reported herein were near St. Joseph, Swan Lake, and Hannibal. The average distance between recording locations was 11 km.

Assuming various crustal models characterized by continuous velocity-depth functions, ray theory was used to calculate travel-time curves and amplitudes for the compressional phases. Several features of the observed travel-time and amplitude data can be explained by these ray-theory calculations. For example, measurements of seismic waves from the three shot points in northern Missouri gave three good amplitude-distance curves for the  $P_g$  phase where this phase was observed as a first arrival. A characteristic of all three curves is a sharp decrease of amplitude, followed by a sharp increase, in the distance range 140-160 km. Such a feature can be explained by changes in compressional-wave velocity of only a few hundredths of a kilometer per second in the upper part of the crust. Large-amplitude secondary arrivals that commonly are correlatable over only a few tens of kilometers at most can be explained by similar small velocity changes within the earth's crust.

# A REVIEW OF RUSSIAN WORK IN MAGNITUDE DETERMINATION.

William Stauder, S.J. VESIAC Conf. on Magnitude Determination, Univ. of Mich., May 1964, pp. 13-32.

Abstract: The Russian development of the M scale has been seen to be quite similar to the development in other countries. Soviet seismologists, however, have used to a greater extent formulas for surface waves of the form

$$M = \log \frac{A}{T} - \log \frac{A}{T}^*$$

rather than

$$M = \log A - \log A^*$$

A more significant development is the work that has been done in devising an energy scale. A practical method has been worked out for the epicentral range  $0 < \Delta < 700$  km whereby an energy class, K, is determined for any given earthquake. The K number is related to energy by

$$K = \log E \text{ (joules)}$$

It remains to extend the scale to greater epicentral distances.

## List of Papers Published

- Cox, Allan, and William Stauder, S.J.  
 "Geometrical Properties of Groups of Fault Plane Solutions," Bull. Seism. Soc. Am., 54: 87-104.
- Dowling, John and Otto Nuttli  
 "Travel-Time Curves for a Low-Velocity Channel in the Upper Mantle," Bull. Seism. Soc. Am., 54, 1981-1991.
- Fernandez, Luis M., S.J.  
 The Determination of Crustal Thickness from the Spectrum of P Waves. Scientific Report No. 13, Sept. 1965, prepared for Air Force Cambridge Research Laboratories, OAR, under Contract AF 19(604)-7399, ARPA Project VELA-Uniform. AFCRL 65-766.
- Fuchs, Karl  
 The Transfer Function for P-Waves for a System Consisting of a Point Source in a Layered Medium. Scientific Report No. 12, July 1965, prepared under Contract AF 19(604)-7399 of Air Force Cambridge Research Laboratories for ARPA Project VELA-Uniform. AFCRL-65-526.
- Hannon, W. J.  
 "An Application of the Haskell-Thomson Matrix Method to the Synthesis of the Surface Motion Due to Dilatational Waves," Bull. Seism. Soc. Am., 54: 2067-2080.
- Hannon, Willard J.  
 Some Effects of a Layered System on Dilatational Waves. Technical Report 3, July 1964, prepared for Air Force Cambridge Research Laboratories, OAR, under ARPA Project VELA-Uniform. AFCRL Rpt. No. 64-614.
- McEvelly, T. V.  
 "Central U.S. Crust-Upper Mantle Structure from Love and Rayleigh Wave Phase Velocity Inversion," Bull. Seism. Soc. Am., 54: 1997-2015.
- McEvelly, T.V., and William Stauder, S.J.  
 "Effect of Sedimentary Thickness on Short-Period Rayleigh Wave Dispersion," Geophys., 30, 198-203.
- Nuttli, Otto, and Thomas V. McEvelly  
 "The Response Characteristics of the Long Period Seismographs of the Saint Louis University Network," Earthquake Notes, Vol. XXXII, Sept.-Dec. 1961, 27-36.



Nuttli, Otto and John D. Whitmore

"On the Determination of the Polarization Angle of the S Wave," Bull. Seism. Soc. Am., 52: 95-107.

Nuttli, Otto

Some Effects of the Crust and Free Surface on the Amplitudes of Body Waves. VESIAC Conf. on Variations of the Earth's Crust and Upper Mantle, July 1964, pp. 5-18.

Nuttli, Otto

"Some Observations Relating to the Effect of the Crust on Long-Period P-Wave Motion," Bull. Seism. Soc. Am., 54: 141-149.

Nuttli, Otto

"The Determination of S-Wave Polarization Angles for an Earth Model with Crustal Layering," Bull. Seism. Soc. Am., 54: 1429-1440.

Nuttli, Otto, and Abou-Bakr Ibrahim

A Method for Determining the Time of Onset of S Waves of Shallow Earthquakes at Intermediate Distances. Paper presented at the Annual Meeting of the Seismological Society of America, Seattle, Washington, March 28-30, 1964.

Ochoa, Daniel E., and William Stauder, S.J.

"The Focal Mechanism of Two Peruvian Earthquakes," Pure & Applied Geophysics, 58 (1964/II): 114-122.

Papazachos, Basil C.

"Dispersion of Rayleigh Waves in the Gulf of Mexico and Caribbean Sea," Bull. Seism. Soc. Am., 54: 909-925.

Papazachos, Basil

"Angle of Incidence and Amplitude Ratio of P and PP Waves," Bull. Seism. Soc. Am., 54: 105-121.

Stauder, William, S.J., and Carl Kisslinger

Some P and S Wave Studies of the Mechanism of Earthquakes and Small Chemical Explosions. VESIAC Spec. Rpt., Proceedings of the Colloquium on Detection of Underground Nuclear Explosions, August 1962, pp. 125-140.

Stauder, William, S.J.

"S-Wave Studies of Earthquakes of the North Pacific, Part I: Kamchatka," Bull. Seism. Soc. Am., 52, No. 3, 527-550.

Stauder, S.J., and Agustin Udias, S.J.

"S-Wave Studies of Earthquakes of the North Pacific, Part II: Aleutian Islands," Bull. Seism. Soc. Am., 53: 59-77.



- Stauder, William, S.J., and Gilbert Bollinger  
 "P<sub>n</sub> Velocity and Other Seismic Studies from the Data  
 of Recent Southeast Missouri Earthquakes," Bull.  
 Seism. Soc. Am., 53: 661-679.
- Stauder, William, S.J., and Michael Goodwin  
 "The SE Missouri Earthquake of 3 March 1963," Earth-  
 quake Notes, 34 (Sept.-Dec. 1963): 74.
- Stauder, William, S.J., John Dowling and Wayne H. Jackson.  
 The BILLIKEN Calibration Shot in Southeast Missouri.  
 Scientific Report 4, August 1964, prepared for Air  
 Force Cambridge Research Laboratories, OAR, under Con-  
 tract AF 19(604)-7399 for ARPA Project VELA-Uniform.  
 AFCL 64-659.
- Stauder, William, S.J.  
 A Review of Russian Work in Magnitude Determination.  
 VESIAC Conf. on Magnitude Determination, Univ. of  
 Mich., May 1964, pp. 13-32.
- Stauder, William, S.J.  
 "A Comparison of Multiple Solutions of Focal Mechanisms,"  
Bull. Seism. Soc. Am., 54, 927-937.
- Stauder, William, S.J.  
 The Present Status of Fault Plane Solutions from P and  
 S Waves and the Relation of These Solutions to Tectonic  
 Stress Field, Proceedings VESIAC Conference of Focal  
 Mechanisms, La Jolla, March 1965 (in press) University  
 of Michigan.
- Stauder, William, S.J.  
 The Direction of Crustal Movements Indicated by Earth-  
 quake Data. Paper delivered at the Research Symposium,  
 Annual Meeting of the AAPG-SEPM, New Orleans, April  
 26-29, 1965.
- Stewart, S. W., and William Stauder, S.J.  
 Application of Continuous Velocity-Depth Functions to  
 Interpretation of Crustal Refraction Data in Missouri.  
 Paper presented at Seismological Society of America  
 Meeting, Seattle, Wash., March 1964.
- Udias, Agustin, S.J.  
 "A Least Squares Method for Earthquake Mechanism De-  
 termination Using S-Wave Data," Bull. Seism. Soc. Am.,  
 54, 2037-2047.
- Udias, Agustin, S.J., and William Stauder, S.J.  
 "Application of Numerical Method for S-Wave Focal  
 Mechanism Determinations to Earthquakes of Kamchatka-  
 Kurile Islands Region," Bull. Seism. Soc. Am., 54,  
 2049-2065.

Abstract (Cont'd)

4. Focal mechanism determinations. Radiation patterns of P and S waves are found to be characteristic of given earthquake sequences and, to some degree, of given earthquake regions.

5. Focal depth. The  $P_g$ - $P_n$  vs  $S_g$ - $P_g$  method has been found of qualitative help in studying focal depth of shocks in SE Missouri. The transfer function for a source in a layered medium has further shown that at shallow depths the source-crust system acts as a rejection filter for the low frequency portion of the spectra of body waves.

6. Inversion of body wave data. The transfer function of TW/TU (ratio of vertical to horizontal ground motion) has been calculated as a function of a dimensionless frequency for representative one- and two-layer crustal models. Spectra of observed P waves are then compared to the theoretical curves to determine crustal structure.

7. Effect of low velocity channels on travel times. Parameters of a low velocity channel have been systematically varied to examine the circumstance under which the channel produces or does not produce a shadow zone. LILBY and GNOME data were then examined to study lateral variations in upper mantle velocities throughout the central, eastern, and western U.S.

8. Local crustal structure, seismicity,  $P_n$  velocity.

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(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Saint Louis University St. Louis, Missouri		2a. REPORT SECURITY CLASSIFICATION Unclassified	
3. REPORT TITLE Investigation of Phase Velocities of Long Period Surface Waves and Focal Mechanism Studies.		2b. GROUP	
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Final Report			
5. AUTHOR(S) (Last name, first name, initial) Stauder, William, S. J., and Otto Nuttli			
6. REPORT DATE September 1965	7a. TOTAL NO. PAGES 40	7b. NO. OF PAGES	
8a. CONTRACT OR GRANT NO. AF 19(604)-7399	9a. ORIGINATOR'S REPORT NUMBER(S)		
b. PROJECT NO. 865201			
c. TASK DOD ELEMENT 62506015	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)		
d. no subelement	AFCRL-65-727		
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13. ABSTRACT The research conducted under this contract concerned eight general areas of investigation: 1. Establishment of a network of seismic stations in the central U.S. suitable for the study of long period surface waves and other specialized studies. 2. Phase and group velocity studies of surface waves. These include phase velocity determinations of both Love and Rayleigh waves, inversion of the velocity data, group velocities of very short period Rayleigh waves, and group velocities along paths which cross the Caribbean Sea. 3. Reduction of ground motion to motion in the incident wave. Theoretical work by Haskell has been verified from observational data and further developed to study angles of incidence of P waves and polarization of S waves which traverse a multilayered crust. Crustal transfer functions for various crustal models have been determined and used to study the effect on ground motion of changes in crustal parameters. (Cont'd)			

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Phase Velocity						
Group Velocity						
Detection						
Crustal Structure						
Upper Mantle						
Incident Wave						
Transfer function						
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